ARMY RESEARCH LABORATORY

The Hardened Subminiature Telemetry and Sensor System Technology Demonstration Phase

W. P. D'Amico
L. W. Burke
U.S. ARMY RESEARCH LABORATORY

R. J. Faulstich
A. Hooper
U.S. ARMY TEST AND EVALUATION COMMAND

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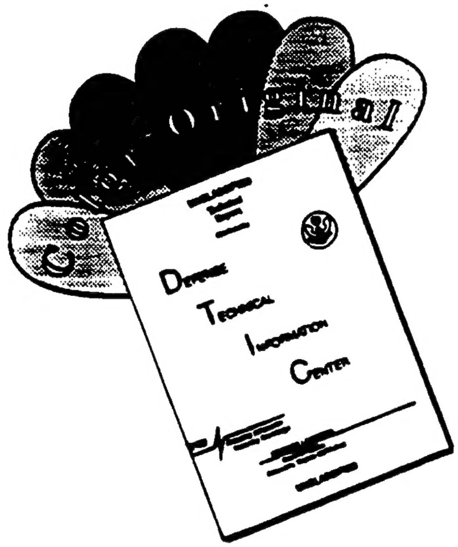

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W. P. D'Amico, L. W. Burke, R. J. Faulstich,* and A. Hooper*

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The Hardened Subminiature Telemetry and Sensor System (HSTSS) program has been a joint effort involving TECOM's Yuma Proving Ground and ARL's Weapons Technology Directorate. This effort centered on the identification and demonstration of a new generation of technologies to support airborne, gun-launched munition test measurements. Funding was provided under the Test Technology Development & Demonstration (TDD&D) program. Presently, the HSTSS effort has progressed into an acquisition cycle where the team has been expanded to include personnel from STRICOM's Program Manager for Instrumentation, Targets, & Threat Simulators. This report documents the status of various technologies at the end of the TTD&D funded portion of the program. This report also serves as a basis and guide for System Enginering/Analysis (SA/E) studies that are to be performed prior to Milestone I/II decision.

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1. INTRODUCTION

The Hardened Subminiature Telemetry and Sensor System (HSTSS) program has been a joint effort involving the U.S. Army Test and Evaluation Command's (TECOM) Yuma Proving Ground and the U.S. Army Research Laboratory's (ARL) Weapons Technology Directorate (WTD). This effort centered on the identification and demonstration of a new generation of technologies to support airborne, gun-launched munition test measurements. Funding was provided under the Test Technology Development and Demonstration (TTD&D) program. Presently, the HSTSS effort has progressed into an acquisition cycle where the team has been expanded to include personnel from STRICOM's Program Manager for Instrumentation, Targets, and Threat Simulators. This report documents the status of various technologies at the end of the TTD&D funded portion of the program. This report also serves as a basis and guide for System Engineering/Analysis (SA/E) studies that are to be performed prior to Milestone I/II decision.

2. BACKGROUND

In-flight measurements for smart munitions, direct- and indirect-fire munitions, missiles, and rockets can be made routine and cost effective with the use of new technologies, many of which are leveraged from Defense Advanced Research Projects Agency (DARPA) investments or commercial-off-the-shelf (COTS) products. In-flight measurements for high-g systems have not been the rule-of-thumb in the past. Continuous measurements of munition attitude, pressure, temperature, and vibration are examples of critical test data that will guide the successful development and type classification of new munitions, especially smart munitions. These flight data are extremely important in view of our reliance on smart munitions and missiles where internal functions can only be determined through on-board flight instrumentation—external tracking by radar or high-speed cameras will not provide the necessary data. It is important to note that these flight data (gathered in a so-called "cooperative mode") should be then convolved with the standard ground-based (so-called "noncooperative mode") data. The outline of the HSTSS approach is summarized as:

Principle:

- Low-cost airborne measurements
- Devices available Department of Defense (DOD) wide

Philosophy:

- Design systems for high shock
- Use DARPA and COTS technologies where possible

Benefits:

- Integrated systems available
- Components available.

A one-page description of the HSTSS program is shown in Figure 1 and is a replication of a program flyer developed for the October 1995 Association of the United States Army (AUSA) Annual Meeting. This report provides additional technical depth, background, strategies, and references.

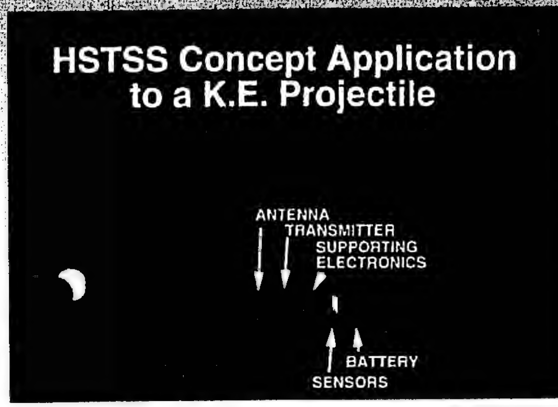
The HSTSS program has been developing a new generation of measurement technologies for projectile and smart munition testing. This program is unique in that all key aspects of an airborne measurement system (transmitter, power supply, sensors, and electronic packaging) are addressed in one effort. There have been programs that are similar in part to the HSTSS program. One such example is the Subminiature Telemetry (SMT) effort by Eglin AFB (Cullen and Keller 1995; Thrusby and Shirley 1995). The SMT program was initiated in 1989 and completed in FY94 under the Central Test & Evaluation Investment Program (CTEIP) under Office of the Secretary of Defense (OSD). This effort focused on the development of a programmable, multichannel data acquisition system and a mode-selectable S-band (2.2–2.4 GHz) transmitter (FM, digital, or spread spectrum) where the chip components were packaged using a green tape (cofired ceramic) MCM process into a 2-inch-square flat pack approximately 0.375 inch high. No sensor or power supply efforts were included in the SMT program, but clearly the transmitter and data acquisition system were highly valuable and useable technologies. The green tape MCM technique requires lengthy design and fabrication time with very difficult rework procedures if repair or modification of finished assemblies is required. Typically, the green tape MCM process is well suited to very high production quantities, and it is not clear that a "universal" measurement system can be achieved in capability or geometry for test and evaluation (T&E) applications.

The spread spectrum mode of transmission provides the capability to track multiple sources at the same frequency (this modulation scheme is what is used in the global positioning system [GPS] navigation), but new ground station equipment is required. The original airborne demodulator (the spread spectrum ground receiver located in an aircraft) was capable of tracking only four transmitter sources and

Hardened Subminiature Telemetry & Sensor System

HSTSS

A technology development and demonstration effort has been underway to provide a new generation of devices and products for in-flight instrumentation of gun-launched projectiles and munitions, especially smart munition systems. Gun-launched systems experience high accelerations (high-g's) and are always very difficult to instrument. The Hardened Subminiature Telemetry and Sensor System program (HSTSS) has been part of the Test Technology Development and Demonstration (TTD&D) Project sponsored by the Director of Test Facilities and Resources, OSD. HSTSS is producing high-g qualified telemetry components, power supplies, high density electronic packaging, and physical sensors such as accelerometers, angular rate sensors, etc.



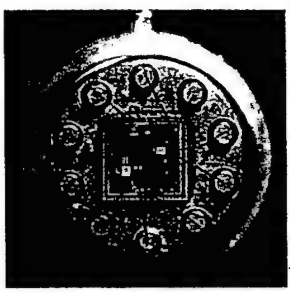
HSTSS OUTLINE

GOAL:
- Low Cost Airborne Measurements
- Devices Available DoD-wide

PHILOSOPHIES:
- Design Systems for High Shock
- Use ARPA & COTS Technologies

PRODUCTS:
- Integrated Systems Available
- Components Available

The overall goal of this program is to make these measurement technologies affordable and available to the ARMY, and to all DoD agencies. The Hardened Subminiature Telemetry and Sensor program is a joint program involving TECOM's Yuma Proving Ground, ARL's Weapons Technology Directorate, and STRICOM's Program Manager for Instrumentation, Targets, and Threat Simulators.

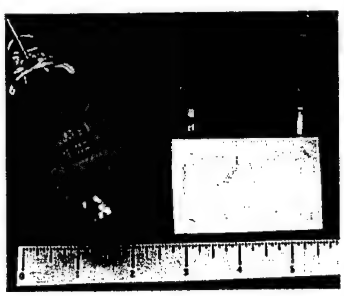


HIGHLY MINIATURE SENSORS

PROVIDE MINIATURE/RUGGED SENSOR SYSTEM

MICROELECTROMECHANICAL (MEM) DEVICES:
- Extend MEM Technology for High-G Use
- Apply Existing "Automotive" MEM's

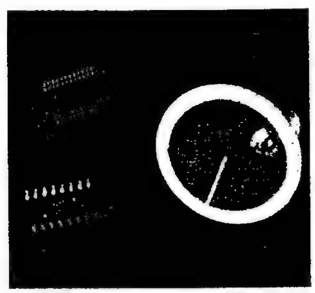
INERTIAL SPIN SENSOR



POWER CELL TECHNOLOGY

PROVIDE UNIQUE "BATTERIES"

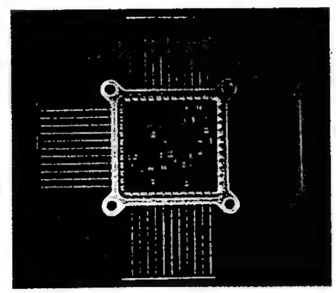
RECHARGEABLE POLYMER CELLS
- Flexible Thin Sheets
- Survived Shocks of 80,000 G's
- 3 Times the Energy Density of NiCd's



TELEMETRY LINKS

PROVIDE LOW COST AND RUGGED TELEMETRY LINKS

USE "MOBILE COMMUNICATION" DEVICES
- Frequency Selection & Power Options
- Spread Spectrum Available
- Components in Plastic or Die Form



PROGRAMMABLE MULTI-CHIP MODULE [MCM]

PROVIDE HIGH DENSITY ELECTRONIC PACKAGING

SUBSTRATES ARE:
- Available in Advance
- Available Many Geometries

SUCCESSFUL TESTS TO 20,000 G's

Figure 1. HSTSS summary description.

was very costly ($240,000). The Integrated Telemetry Package (ITP) was demonstrated successfully at a range of 9 km. A second CTEIP/TTD&D effort of $900,000 was initiated in FY94 to reduce the price of the demodulator to $4,000/unit "in quantity." This effort is balanced by a $3.2-million Wright Laboratory Armament Directorate 6.3 effort. Eventually the IPT cost is desired to be $500/unit "in quantity." All contract efforts have been conducted by the Harris Corporation. An SMT package is shown in Figure 2.

It is clear that the philosophy of the HSTSS program is somewhat patterned after the SMT effort except with a broader focus to include sensor and power supply technologies and to assure that all components and final systems can be qualified at high-g's. When possible, the HSTSS program will adapt various commercial technologies in order to mitigate both cost and single-vendor proprietary issues. The harsh gun launch environment coupled with small and variable volumes in projectile systems drive the requirements and philosophies of the HSTSS effort.

3. TYPICAL APPLICATION SCENARIOS FOR HSTSS

3.1 Direct-Fire Tank Ammunition. Consider the development and test of a kinetic energy projectile. Here is an extreme example for the application of on-board instrumentation. The sabot structure must support the long slender rod during travel down the bore and release the penetrator into free flight so as to assure a high probability of first-round hit. If accuracy or lethality deficiencies occur, what are the means by which test and development engineers identify the root cause? If recently manufactured ammunition does not initially pass a lot acceptance test, what are the testing options?

Typical external measurement systems such as target cloth screens, yaw cards, high-speed video or framing cameras, x-ray cassettes, and radars may not provide sufficient detail as to projectile angular motion and spin. Most of these data are only available at discrete locations, rather than in a continuous stream. Additionally, the initial motion of the tank gun and the exhausted propellant gases yield difficult conditions for external measurement systems at launch where the initial conditions of the projectile are established. Labor-intensive setups and hand reductions of yaw card and target cloth data can be eliminated through the use of on-board instrumentation. If the flight history is normal, then the penetrator slices through the target cloth and yaw cards, leaving neat patterns reflecting the six-bladed fin set. What if the target cloths reveal anomalous patterns? Our present test technology leads to "forensic engineering" or guessing at both the problem and the solution. Lengthy and expensive retesting can occur.

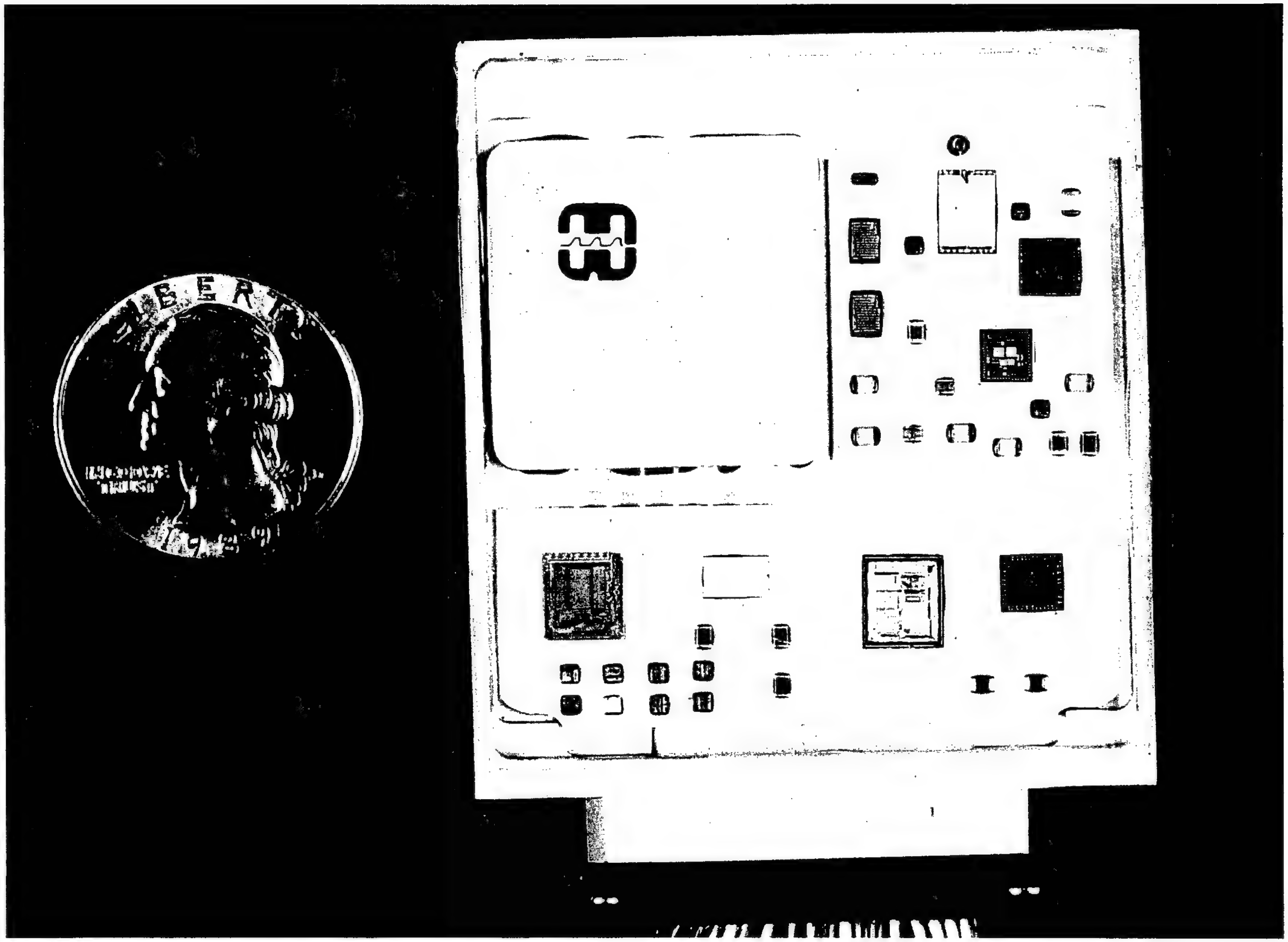


Figure 2. An SMT package from the Eglin AFB effort.

It is virtually impossible to instrument a monolithic rod—it is all metal—yet all direct-fire ammunition is fitted with tracers as an aiming aid for combat operations. It is possible to replace the tracer with an on-board instrumentation system. This system would need to be extremely small and rugged. It must withstand a launch environment of axial accelerations that are 50,000 times that of gravity and very high propellant flame temperatures and pressures. In fact, a pre-HSTSS demonstration of a tracer well telemetry system was made by Burdeshaw and Clay (1991). Based upon unique in-house technologies from Motorola, a 5.5-GHz tracer well system was successfully demonstrated. This system carried no sensor, although the "AM-ing" of the AGC (Automatic Gain Control) signal was processed to obtain spin (Figure 3). This technology was not pursued since it involved a very nonstandard transmitter (free-running and highly unstable center frequency) and custom ground receiver that were proprietary to Motorola. At this point, it was also clear that substantial investments in microelectromechanical (MEM) sensors must also be made in order to provide a wide range of measurements (Bryzek, Petersen, and McCulley 1994).

A conceptual HSTSS measurement system, denoting key subsystems, is shown in a cylindrical piggy-back stack in Figure 1. In the future, the stack of subsystems can be customized to include different measurement capabilities—accelerometer, pressure transducer, spin counter, etc. If in-bore data are needed, a digital delay can be implemented to sample and hold the data during the 15-ms launch cycle. HSTSS has already flight-demonstrated a digital delay. The subsystems must be integrated into a final system and threaded into the tracer well.

The required subsystem components would be selected by the test and development engineers, providing a measurement system that would yield continuous data. These on-board data would then be combined with a radar track to provide an "internal and external" stream of data that engineers can study and interpret in detail. Additionally, these flight data can provide input to engineering models of in-bore propulsion and structural response as well as exterior ballistic trajectory simulations.

The TERM-KE system, currently under test and development, is a prime example of how HSTSS technologies would be applied and would be needed. Figure 4 shows the TERM-KE concept (which is still evolutionary). TERM-KE has a composite material structure that will carry a rocket motor (ignited at launch and operates in a boost, sustain, and boost mode), a kinetic energy rod (not shown in Figure 4), a millimeter-wave terminal seeker, a circumferential ring of solid thruster impulse motors for yaw control and maneuver authority, and all processing electronics and attitude sensors for autonomous flight. There

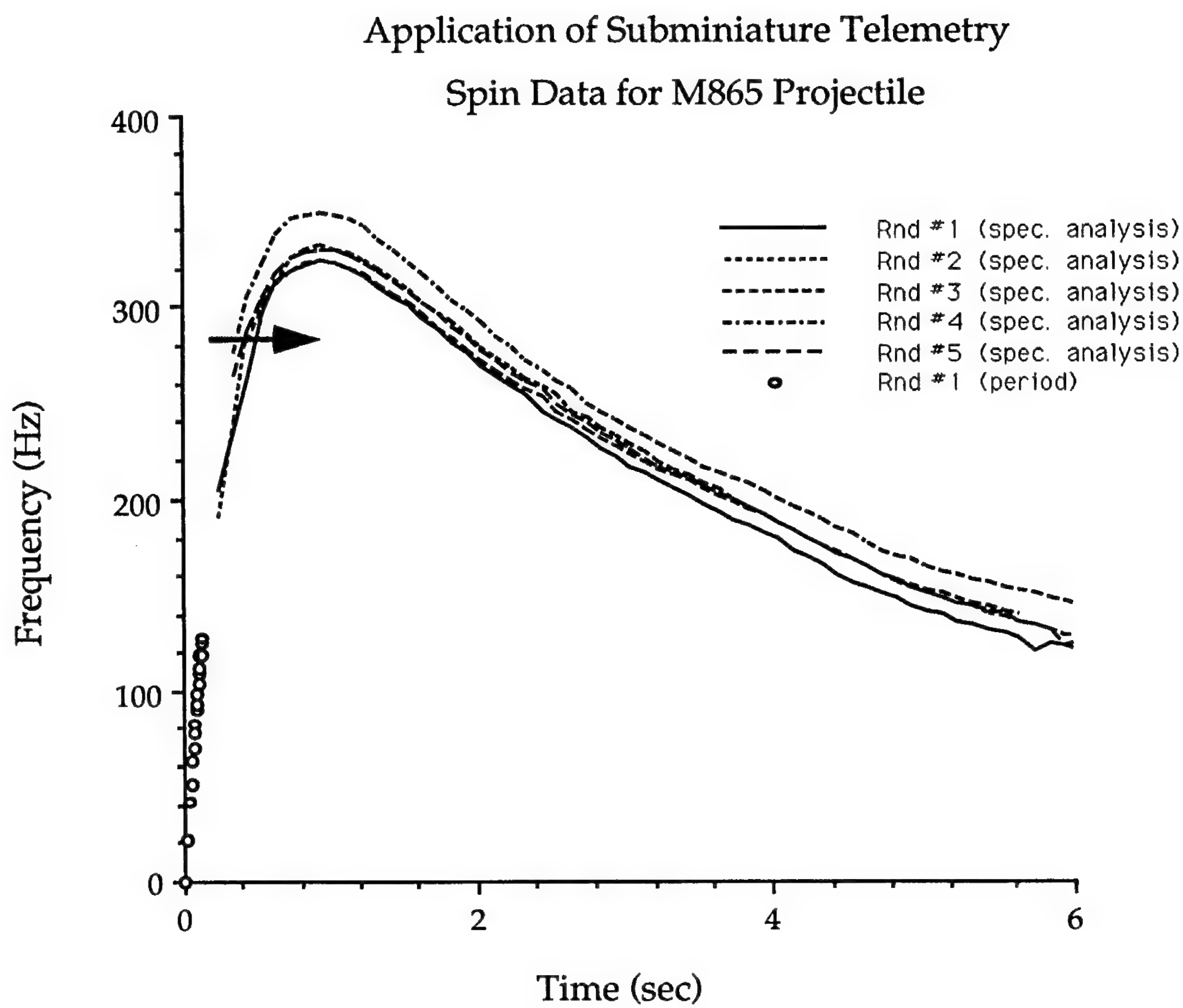


Figure 3. <u>Data from a tracer well system prior to the HSTSS.</u>

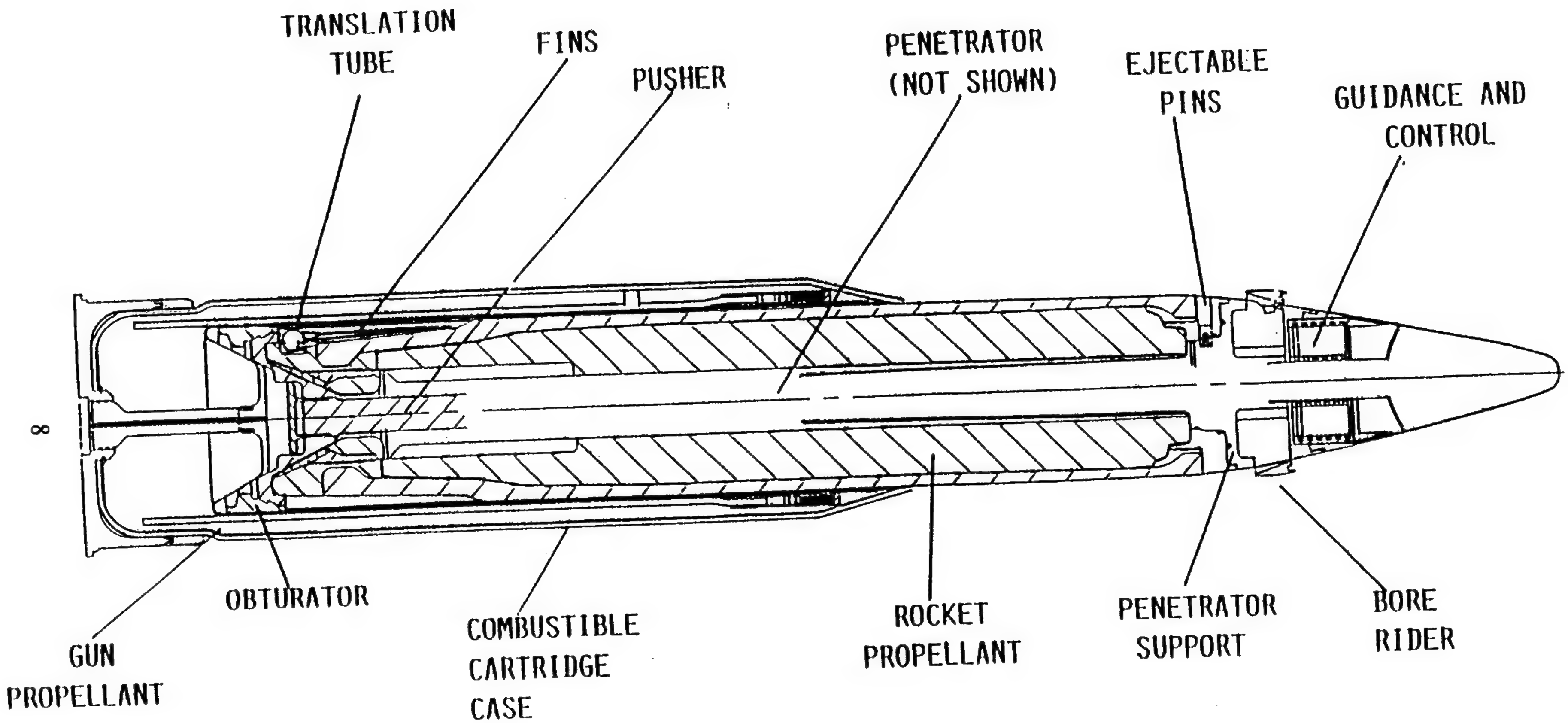


Figure 4. TERM-KE Concept.

have been several on-board T&E measurement systems in the early stages of the TERM-KE program—all unique and expensive. These flight systems were all of different configuration and function, but as the TERM-KE program matures, more systems will be flight tested in a simultaneous fashion. The exact flight configuration of an all-up round (AUR) is not known and cannot be exactly predicted in a long-range plan, and yet the future on-board measurement system must be adaptable and compatible with the evolving AUR hardware. TERM-KE represents a typical application of HSTSS technologies. It should be noted that due to the projectile mass and structural/sensor requirements, TERM-KE launch accelerations are only about 20,000 g's, much lower than a kinetic energy rod.

3.2 Indirect-Fire Systems—Artillery and Mortar Projectiles. A reasonably complete description of artillery systems is required to complement the HSTSS approach. The unique feature of artillery is that it is spin-stabilized (unlike modern tank ammunition that is fin-stabilized). For example, developmental 155-mm diameter systems in most North American Treaty Organization (NATO) countries (the United States included considering the Crusader program and potential 52-caliber-long tubes for Paladin upgrades) will have launch velocities of approximately 1,000 m/s and spin rates of 300 Hz. Although velocity decreases rapidly as the relatively blunt artillery projectile flies down range, spin decreases much less. The launch accelerations for 155-mm systems are presently well below 25,000 g's, but the addition of impulsive and relatively constant centrifugal accelerations provides an additional difficulty. Primarily, this means that offsets or eccentricities for components such as transmitters, sensors, and power supplies must not yield bias-like behavior or failure due to centrifugal accelerations or forces.

Historically, since there are only moderately high-g levels and large available spaces in artillery systems, airborne measurements have been more common. One measurement system that has been somewhat standardized and employed in large numbers is the fuze-configured yawsonde, shown in Figure 5 (Mermagen and Clay 1974). Over 2,500 of these units have been used to simply replace a standard NATO fuze with no other modifications to the projectile system. The yawsonde measures projectile spin and yawing motion about the trajectory by using a pair of masked solar sensors that determine the angular orientation of the projectile with respect to the sun. Details of the pitch, yaw, and roll histories have provided engineers valuable data on down range dynamic behavior and aeroballistic performance.

The yawsonde technique represents an almost "primary" inertial reference that has been used to determine projectile spin, pitch, and yaw. Simultaneous yawsonde data and radar tracks also allow for

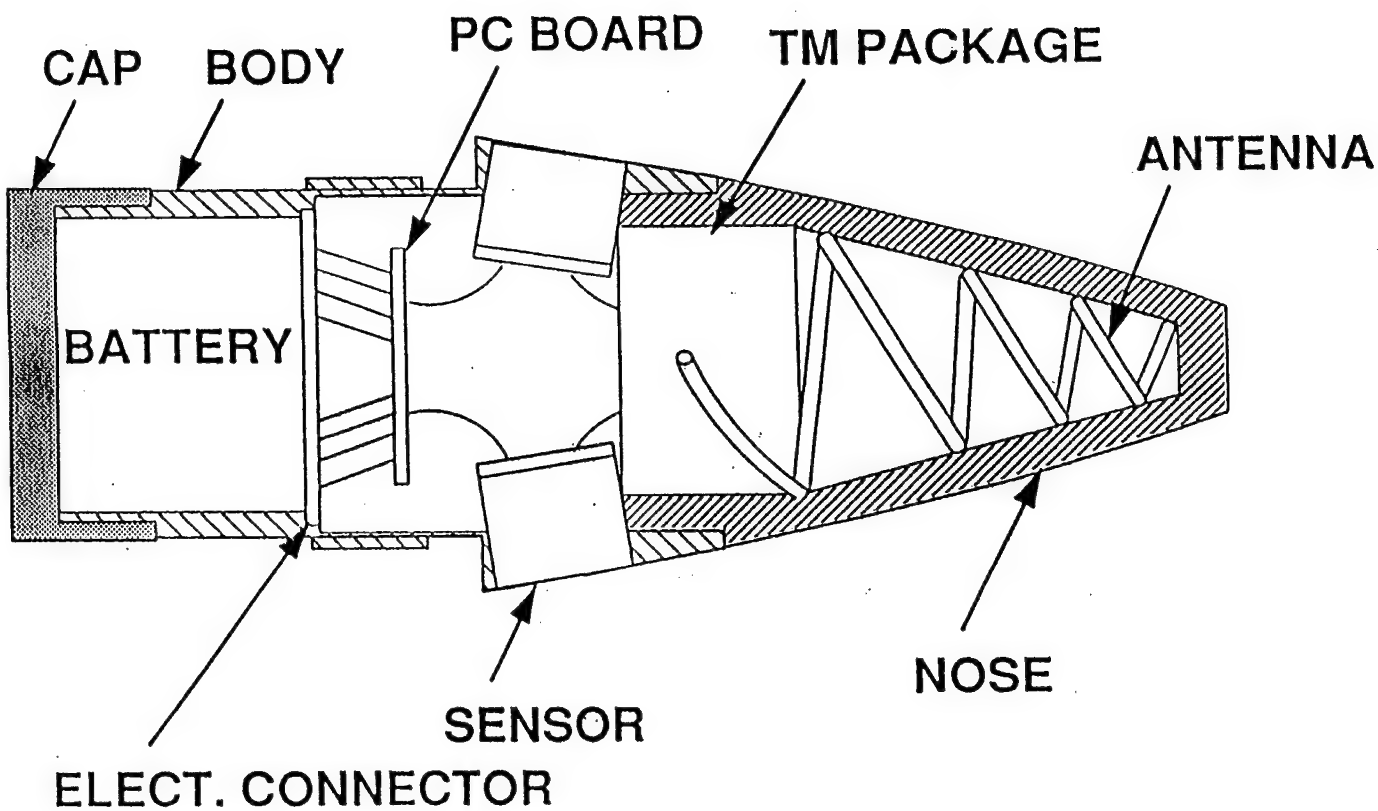


Figure 5. Fuze-configured yawsonde schematic.

the determination of in-flight aerodynamic coefficients (Whyte and Steinhoff 1993). It is envisioned that during the HSTSS development cycle yawsondes will be used to verify and calibrate the operation of MEM accelerometers, gyroscopes, and any other orientation sensors. Plans for combined yawsonde/sensor tests have been and will continue to be part of the HSTSS development cycle.

There are two developmental artillery programs where the application of HSTSS technologies is required—the Low-Cost Competent Munitions (LCCM) program and the 155-mm XM982 program. Figure 6 describes the LCCM program that will produce NATO standard fuze devices that use GPS and MEM-based inertial measurement unit (IMU) technologies as trajectory sensors coupled to maneuver mechanisms (one-dimensional in range or two-dimensional in range and deflection) to reduce normal ballistic errors. The LCCM program has an Air Force/Navy companion program called the Joint Direct Attack Munition (JDAM), which utilizes a GPS/IMU-based canard screw-on module for 1,000- and 2,000-lb bombs. Clearly, it is a sufficiently large challenge to simply package the LCCM or JDAM concepts in the required volumes and shapes, let alone provide additional space for a T&E system. For the LCCM products, an HSTSS system could be fitted to the threads on the end of the fuze where a burster charge would normally be located. This would involve a protrusion into the projectile ogive and would probably eliminate live testing for payload expulsion, but the guidance, navigation, and control (GNC) system operation could be overwatched. Since the LCCM concepts all involve a down link to provide tactical information of projectile position, a separate transmitter for test purposes may not be needed. In fact, it is clear in this example that HSTSS sensor technologies could be used as part of a tactical system, and HSTSS represents a clear possibility for embedded T&E functions within a tactical system.

The XM982, a combined rocket-assisted projectile (RAP) and baseburn (BB) motor, is shown in Figure 7. A standard fuze has recently been specified by the user and will be incorporated into next-generation hardware. The internal fuze provides a portion of the RAP delay sequence, and modifications must be made for compatibility with the LCCM devices. The XM982 has very aggressive precision and accuracy requirements for range and deflection. Simple radar tracks will provide only the first level of data that are required to separate the precision and accuracy errors and their various components. The available space for airborne test components is very small when compared to previous artillery projectiles where fuze and ogive spaces were options. Again, it becomes clear that an integral HSTSS device (probably in a fuze configuration) would be highly useful. The XM982 is presently undergoing an HSTSS cost-benefit analysis.

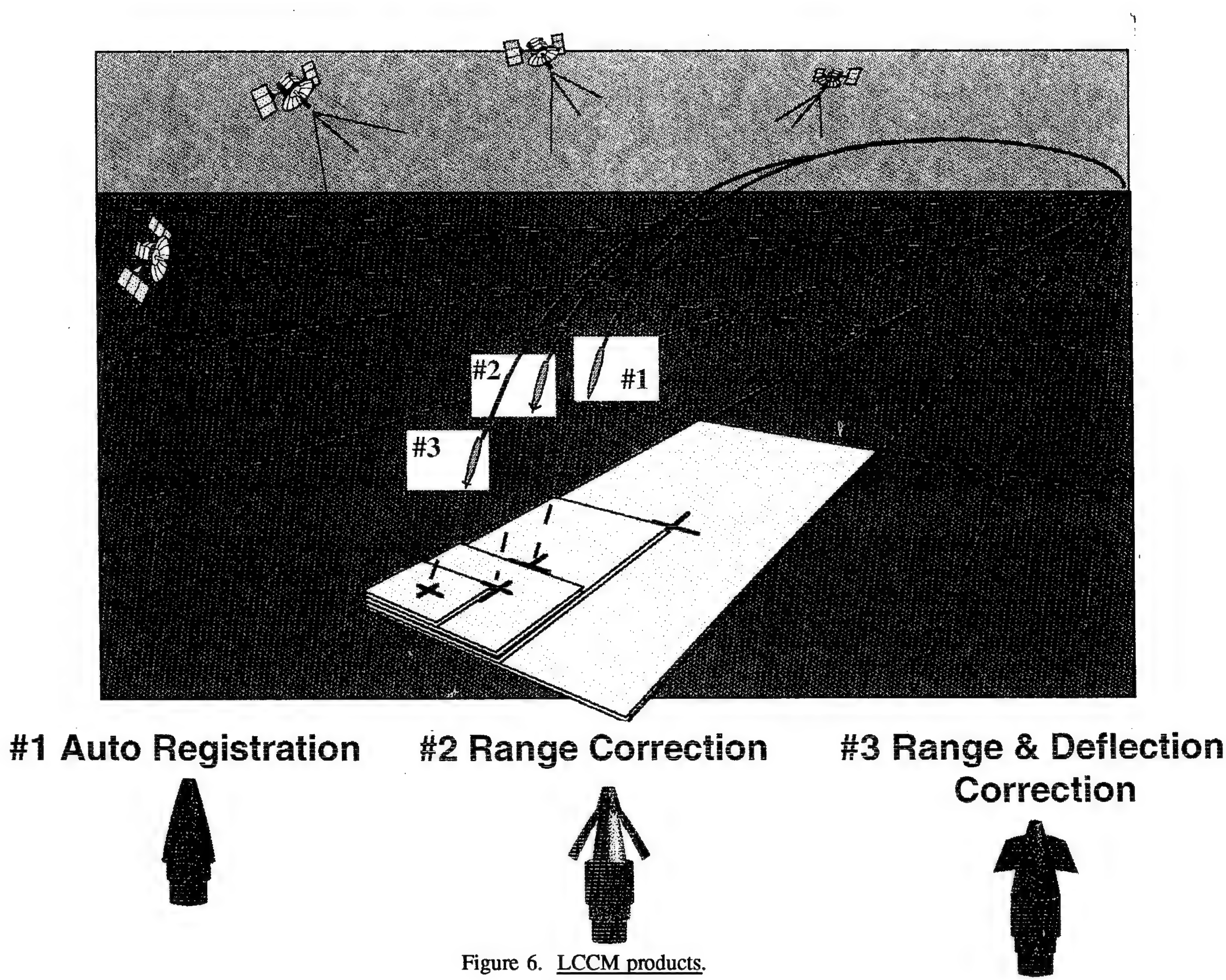


Figure 6. LCCM products.

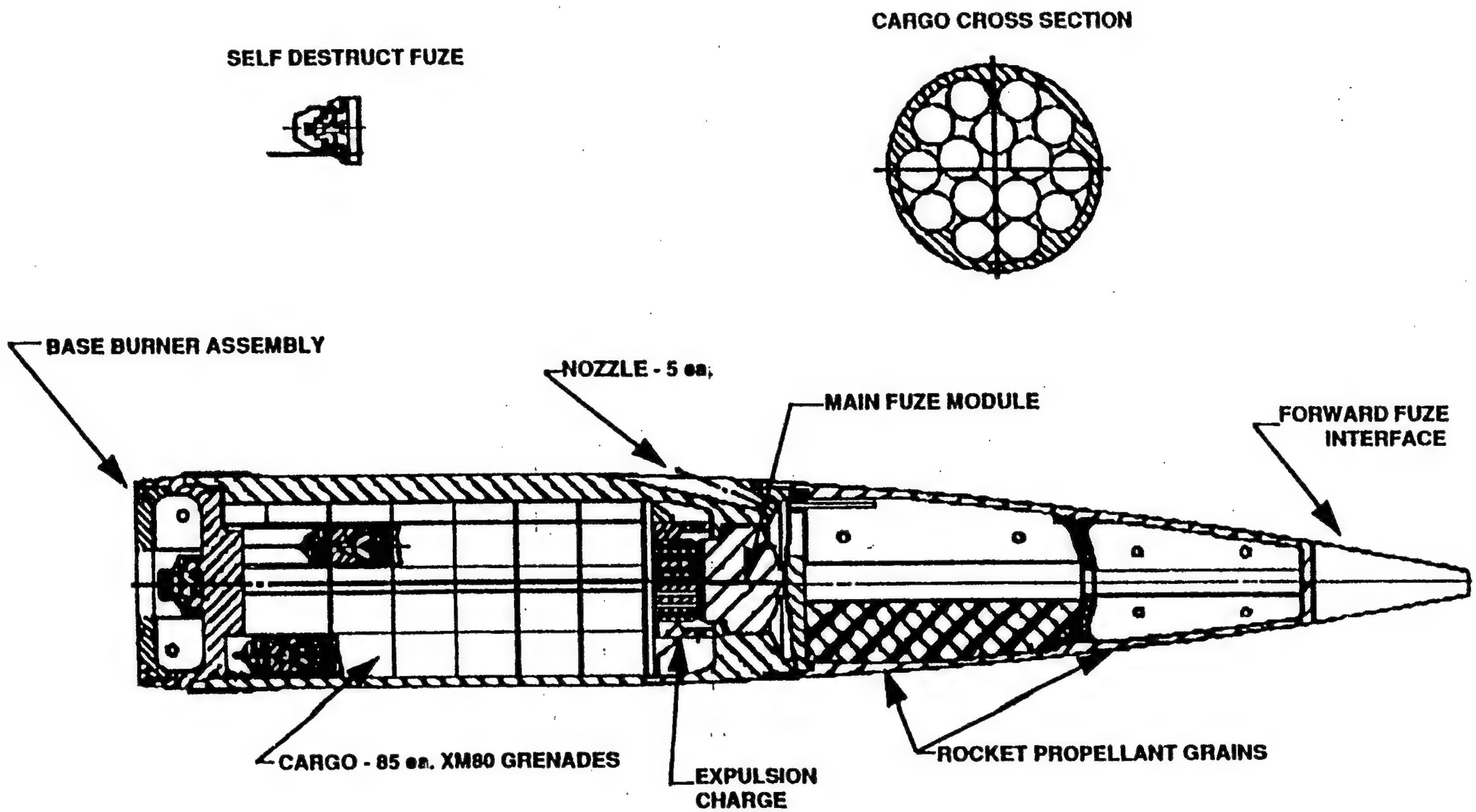


Figure 7. 155-mm XM982 ERA (BB/RAP).

Mortars represent a subset of indirect-fire munitions. Often, it is assumed that mortars do not experience a high-g launch, but that is not the case. Without making detailed calculations, mortar tubes are very short, and launch velocities are nearly at sonic conditions. An 81-mm mortar experiences over 12,000 g's at launch. Efforts to develop precision-guided mortars for top attack of hard or fixed targets must be supported by HSTSS products. Most mortars are fin-stabilized. Mortar fuzes are not similar to artillery fuzes, but it would be expected that an HSTSS fuze could be reconfigured to support mortar testing.

3.3 Missiles and Rockets. Since missiles and rockets are not subject to large launch accelerations, airborne measurements are much more the rule, especially for maneuvering and terminal-seeking missiles. However, the HSTSS products will be of great value since space for airborne measurement systems remains very small and the cost of raw components is very high. There are many complex missile systems where terminal seeking sensors are closed loop with an autonomous guidance-and-control system. Guided missiles are not discussed in detail here, except that many internal functions (voltages for internal power supplies to various components and processors), raw terminal sensor ([IR], millimeter wave, or video), and guidance-and-control parameters are piped to a ground station to understand the performance of on-board processors and algorithms. Such flight data are invaluable early in the development cycle or during stockpile reliability trials. HSTSS would aim to augment and support these ongoing processes and procedures through the use of efficient packaging, inexpensive sensors, and unique power supplies.

For the case of free-flight or ballistic rockets, such as the 2.75-inch multi-Service system, measurements similar to direct- or indirect-fire projectiles have been common. Recently, novel flight tests were conducted for the Navy of an illuminating payload (Brown et al. 1996). Measurements of rocket thrust, projectile drag subsequent to rocket burnout, flight body strain, and flight motion (four sensors to compensate for low roll yawsonde rates) data were made. Rocket axial force measurements were made using an automotive air-bag accelerometer.

3.4 Smart Munitions. Gun-launched smart munitions and projectiles are just emerging for the Army. The first examples are the sense-and-destroy armor (SADARM) submunition and the STAFF projectile. Unfortunately, SADARM represents a critical example where only a few in-flight measurements were made. Initial yawsonde tests to determine the motion of the canister on the parachute system were made (Oskay and Mermagen 1981). It is clear that the agonizing SADARM development and test cycle could have been dramatically improved if HSTSS-type technologies were available, but they were not. It is

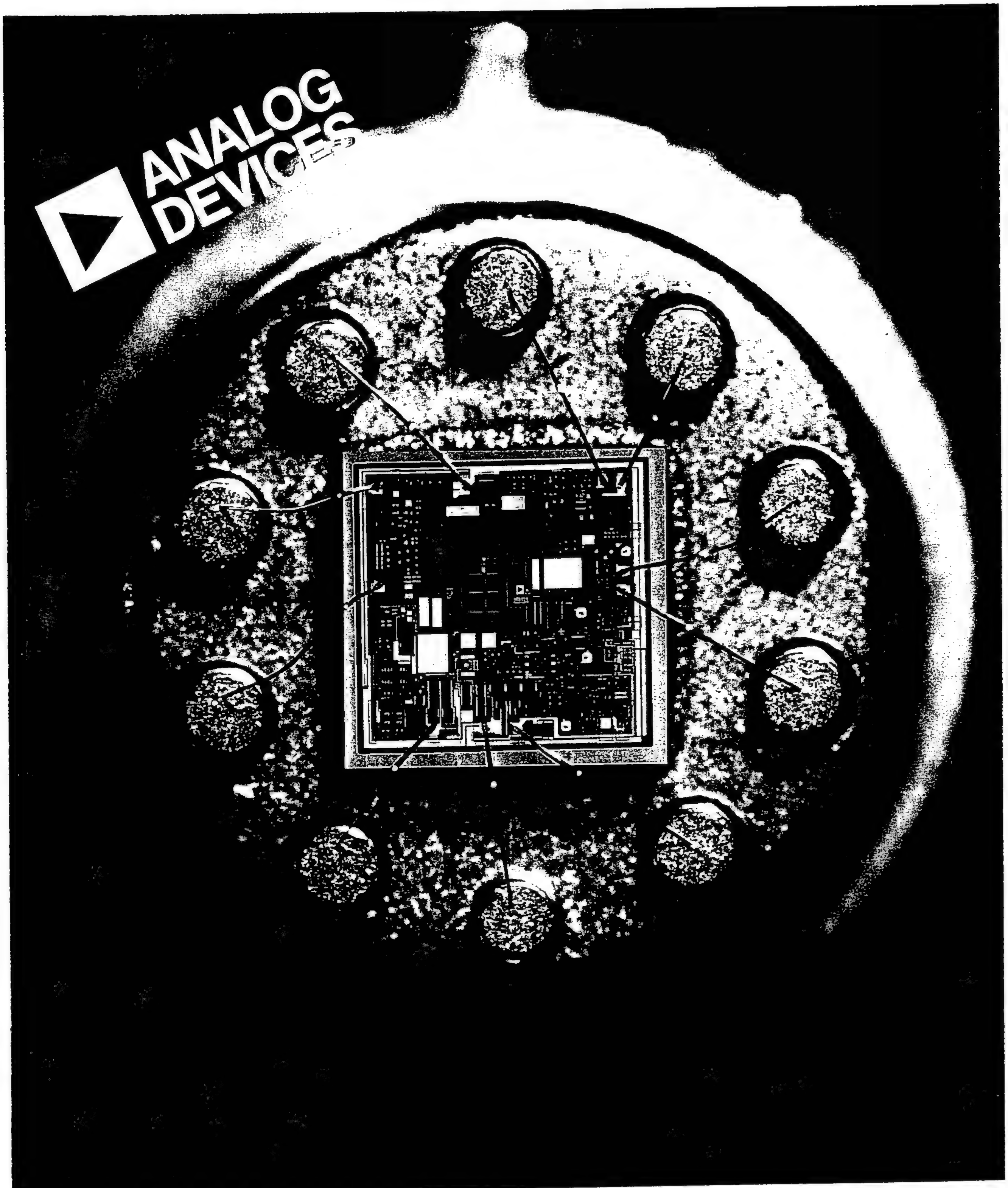
imperative that live submunitions (not inert dummy warheads) be instrumented, providing clear flight data of improved design or product improvements. Again, given little and very irregular space within a live warhead, HSTSS will offer the only practical solution. Telemetry has been more frequently used on the STAFF program.

4. STATUS OF TECHNOLOGIES AT THE CONCLUSION OF TTD&D

The HSTSS technologies are based in four areas: sensors, packaging, telemetry, and power supplies (as shown in Figure 1). The seemingly restrictive and difficult requirement of high-g survival (and at times, operation during high-g) provides a foundation leading to miniature and inexpensive technologies. There are a few basic principles to high-g survival—small wires and connectors, plastic vs. ceramic parts, encapsulation of heavy or unsupported structures, etc. However, the best design principle for high-g is simply size and mass—miniature is best. This naturally leads to electronics and sensors that are produced using practices that are common to integrated circuits (ICs). The use of bare IC dice (unpackaged) components and MEM sensors should naturally lead to small and configurable designs that would lead to high-g survivability. It is now necessary to realize that T&E measurement systems are often one of a kind, requiring only a few finished pieces, and these measurement systems must be available in a short period of time. Hence, rapid prototyping and packaging for a few systems is required, thereby not allowing the use of most MCM processes. It is also clear that many times important components and devices come in "chunks" that are not amenable to available volumes and spaces. Primary examples of this are transmitters and power supplies that typically come in cylindrical shapes. The integration of sensors, conditioning electronics and data acquisition systems, telemetry devices, and power supplies into a functional measurement system requires adaptable and configurable technologies.

4.1 Sensors. HSTSS has focused on highly miniature sensors, many of which are leveraged from the DARPA microelectromechanical or MEM programs. The MEM sensor is produced by etching processes that were derived from the microelectronics industry.

Shown in Figure 8 is a surface micromachined silicon accelerometer from Analog Devices. This commercially available $30 air-bag accelerometer is complete with an electronics die that has been integrated with the sensor die into a single package. This accelerometer has been flight tested as a drag sensor on a 2.75-inch rocket. The in-flight accelerations, when integrated within a trajectory code,



Analog Devices' ADXL-50, the industry's first surface micromachined accelerometer, includes signal conditioning on chip.

Figure 8. MEM accelerometry by Analog Devices.

provided a consistent comparison with radar data (Figure 9). The device when unpowered has been ground tested and has survived accelerations of 60,000 g's. Testing details can be found in Davis (1996). Since an internal calibration and turn-on cycle consume only 2–3 ms, this device should survive a gun-launch in an unpowered mode and could then be rapidly powered up subsequent to muzzle exit to provide a down-range sensor capability. Further ground and flight tests are anticipated during FY96. Other MEM sensors (some from Analog Devices and some from Motorola) have also been tested by Davis (1996).

Another MEM sensor development program by Rockwell Autonetics and Draper Labs is providing the ability to measure angular accelerations with a silicon gyroscope. The sensor die is shown in Figure 10. This sensor has also survived accelerations common to guns when unpowered. Integration of the conditioning electronics with the sensor die is presently underway. Initial applications of this gyro will be in the automotive industry for automatic braking systems. The HSTSS program has been cited as a Technology Reinvestment Program consortium participant with the Rockwell/Draper team in a recently funded DARPA program. This effort will be leveraged by the HSTSS program to integrate the low-g technology into high-g applications and products.

The Rockwell/Draper team is also responsible for several designs of a bulk-machined accelerometer. Under a recent DARPA contract leveraged by HSTSS, several high-g accelerometer systems have been demonstrated. A program summary is provided in Figure 11. First, a single-axis 100,000-g accelerometer is intended to integrate in-bore acceleration and provide muzzle velocity. Other accelerometers survive this high shock and measure in-line and cross-axis accelerations up to 100 g's. These sensor die could be mated with the ASIC for automotive-type applications, providing a wide range of performance and an alternative source for sensors.

Typically, munitions must spin in order to provide aerodynamic stability and accuracy. The presence of spin can disrupt the tracking of angular rate sensors and linear accelerometers whose output is integrated into velocity and position data. An inertial spin sensor technology from Sensor Applications that utilizes a material whose resistance changes in the presence of a magnetic field has been utilized (Davis, Clymer, and Graves 1996). As this element is rotated across the earth's magnetic flux lines, the change in resistance can be amplified and conditioned to produce spin data. The raw die is less than 0.1 inch in length and has already been integrated into a shock resistance plastic package. These packages have survived accelerations up to 30,000 g's, and flight tests are planned in the near future. Isolation from ferrous materials has also been accomplished.

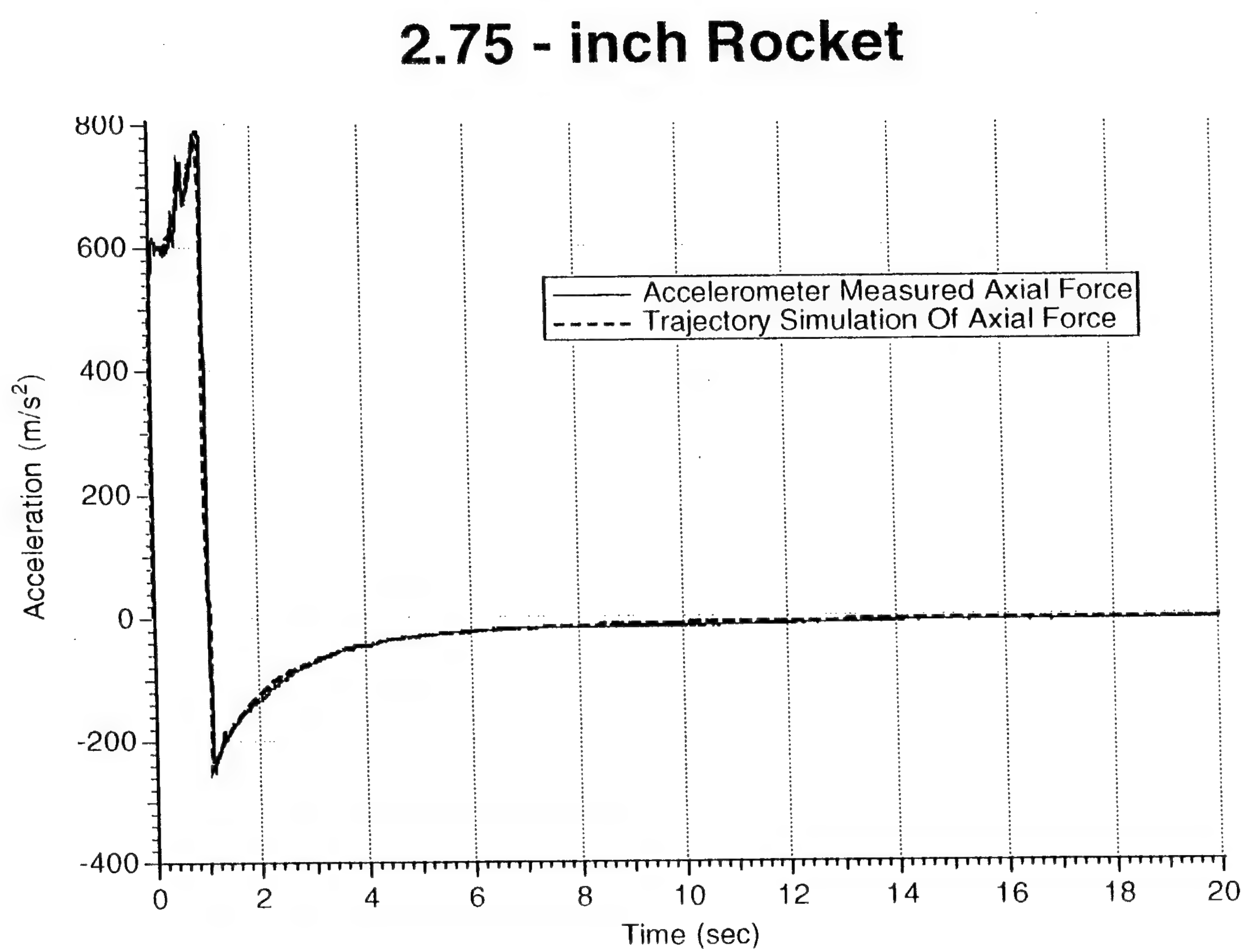
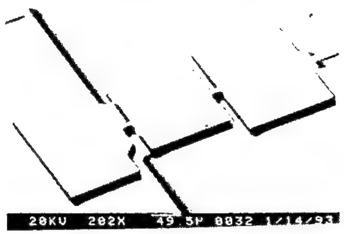


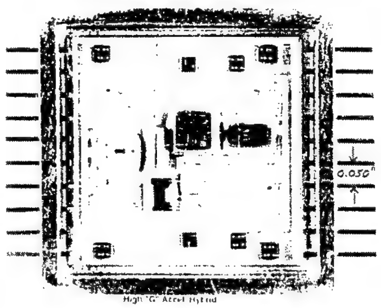
Figure 9. Comparison of measured and calculated axial force.

Figure 10. MEM angular rate sensor die.

4.2 Power Supply Technologies. HSTSS has been developing and testing several power cell technologies for high-g use. Conformal lithium-ion polymer power cells have been under evaluation. These solid-state polymer batteries (nominal 4 V) are rechargeable, lightweight, and environmentally friendly. The cells can be made to conform to almost any user shape or configuration. They can be layered together and internally connected in parallel or series configurations to provide a complete battery system. Ultralife Batteries has been under contract to modify its commercial cells for the gun-launched environment (Burke, Faulstich, and Newnham 1995). To date, single-cell configurations have survived accelerations of more than shocks of 100,000 g's and centrifugal tests at 300 rev/s yielding radial accelerations of 22,000 g's. Research, sponsored by DARPA, is currently being performed to increase the energy density and temperature performance of the cells. Primary power cells are also available from Ultralife Batteries that offer the similar form factor characteristics with even higher energy density. These power cell technologies have major applications in the mobile communications and laptop computing industries where most electronics are moving to 3-V supplies. The high-g designs are not drastically unique and will be the basic technology configuration for these commercial applications.

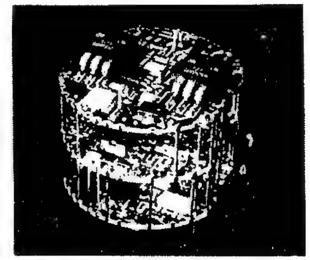
SENSOR





- 100 kg accelerometer
- 70 kg static tested in airgun
- Operational 80 kg test w/elect. Jul 93

ELECTRONICS



- Design Complete
- Bench Tested
- Assembly to air gun piston Jun 93

HIGH-G CENTRIFUGE

- Gov. transfer from Sandia to ARDEC
- 20 krpm, 100 kg
- Installed @ Draper
- Operational Jun 93

PROGRAM STATUS

$1.3 M (8/92 – 9/93)		$1.1 M (9/93 – 9/94)	$1.0 M (9/94 – 9/96)
8/92 – 1/93	1/93 – 9/93	9/93 – 9/94	9/94 – 9/95 – 9/96
PHASES			
I	II	III	IV
• High-G Accel. • Centrifuge • Air Gun		• Lo-G Accel. • Centrifuge • Air Gun	• Mixed Accel. Array • MCM Packaging; • Centrifuge • Air Gun • Flight Test

- On schedule, on budget, 90% complete

Figure 11. Draper MEM accelerometer effort.

4.3 Programmable Multichip Modules (MCMs). Multilayer printed circuit board technology is the most common format for high-density packaging of electronic components and circuits. Higher density packaging techniques exist, but they involve long and costly design and manufacturing processes. To allow for the rapid prototyping of electronic systems, two commercially available MCM technologies have been under evaluation (O'Brien and Pratser 1994). Both of these MCM technologies are electrically programmable and allow for the direct placement of raw die onto a premanufactured substrate. One substrate technology by PICO Systems uses an antifuze technology and is silicon based (Burke et al. 1994). Circuit connections within the substrate are programmed by disabling the antifuzes to produce internal circuit paths or vias. The die are then attached by normal wire bonding techniques to the substrate. A PICO Systems MCM package has been flight tested at an acceleration level of 20,000 g's with both analog and digital components as part of the measurement system (Ferguson et al. 1996).

A second vendor, the Microelectronics Computer Technology Corporation, offers a rapid prototyping technology that utilizes a laser customization tool, creating custom circuitry on a generic thin film substrate. As before, the die are attached to the MCM using standard wire bonding methods. These substrates offer a wide variety of geometrically flexible shapes and high packing densities. Bare substrates from MCC have survived laboratory shock testing in excess of 30,000 g's.

Both of these technologies are cost effective as low-volume (several hundred units), high-density MCM schemes. In both cases the substrates are premanufactured and stocked. They do not require lengthy fabrication/assembly procedures or expensive masking or clean room processes. For each vendor, a computer-aided design system imports the desired circuit functionality, programs the substrates, and outlines foot prints for die placement. A digital delay (ostensibly for use as an in-bore data acquisition scheme) was demonstrated on the PICO flight test. Clearly, these MCM technologies could be used to fabricate a fight recorder in cases where telemetry is not needed or inappropriate. An electrical characterization was conducted by Borgen (funded by HSTSS) on these two substrate technologies (Borgen 1995). Measurements for cross-talk and frequency response were made. Conclusions as to a "best" substrate should be reserved on the basis of design/fabrication time, cost, and higher shock survivability. It is possible that both technologies have distinct advantages.

It is clear, however, that the use of programmable substrates provides for continued growth of the HSTSS products and devices since new IC technologies can simply be incorporated. For example, rapid developments in field-programmable gate arrays (FPGAs) will produce a new level of adaptability in the

design of data acquisition and measurement systems. Also, if substantial on-board processing of data are needed, then RASSP-type (rapid prototyping of application specific signal processing) devices could also be integrated into follow-on HSTSS products.

4.4 Transmitters and Data Links. The portable communications industry is rapidly developing new devices and products. Wireless communication systems, local area networks, cellular phones, and mobile links are common at frequencies not permitted on test ranges. HSTSS engineers are working with communications companies to survey the use of existing commercial technologies at the common L- and S-band frequencies. One industry leader, M/A-COM, is currently under contract to aid in this process. Preliminary evaluations indicate that technologies that are common to "cellular phone" systems can meet many of the IRIG standards of frequency allocation, stability, and bandwidth. Presently, link budgets and analyses are underway to complete this preliminary survey.

Under the HSTSS program, ARL engineers have considered the use of high-frequency (1–10 GHz) variactor-tuned oscillators. These devices have been biased to form a low-cost FM transmitter, and bench tests have been conducted to investigate frequency stability, power, and bandwidth. This is a very low budget ($300 with gain block) solution for very small and simple transmitter requirements such as a tracer well system. It is not clear that the HSTSS program should attempt to design a specific digital transmitter to a custom single state. It may be more efficient to demonstrate that "re-engineered" commercial sector technologies customized to military frequencies may be a cost-effective and timely solution. In the out years, new transmitters can simply follow new technologies and continue to improve in performance.

4.5 Time/Space/Position Information (TSPI) and GPS/IMU Technologies. It may at first seem strange that HSTSS has not invested in the application of GPS technologies to overtly and specifically obtain TSPI data. That actually has been a conscious effort—not to fund GPS during the development and demonstration phases of HSTSS. It was clear to the HSTSS team that commercial advances in GPS would occur and that several tactical programs—such as the LCCM program previously described—would provide parallel-funded efforts that simply could be leveraged into the HSTSS plan (Wiles 1992; Smuk et al. 1994). It is not clear whether the use of GPS translator or receiver technologies would be more advantageous, and this may be a case-by-case decision based upon test requirements. For the T&E mission, real-time TSPI data are not always needed; hence, it can be considered that TSPI data sources are combined subsequent to the actual flight test. If details of the flight vehicle motion are needed (more than just center-of-gravity, but spin, pitch, and yaw), then a suite of inertial sensors (an inertial

measurement unit or [IMU]), radar, GPS (receiver or translator, clear access [C/A] or precision military code [P]) should be used. The bandwidth requirements of a C/A transponder is significant (1 MHz), while reduced position, velocity, and time data from a GPS receiver, if retransmitted, would be very narrow band. Overall power and transmitter requirements are substantially impacted by the inclusion of the type of GPS/IMU technology selected or available.

A miniature high-g GPS C/A code translator has been demonstrated by the ARL Sensors Directorate under the LCCM program. It is anticipated that miniature high-g GPS receiver technology (3 inch^3 and 3 W) will be demonstrated in the next several years. A critical technology for a stable crystal oscillator system is required for a high-g GPS receiver. A potential solution has been suggested by Filler and Vig (1995). It may be short sighted, however, to simply include GPS data (translated or reduced) into an overall data stream containing other measurements. It is clear that the combination of a GPS system and other on-board data could be accomplished in a more integrated fashion, thereby taking advantage of the existing GPS transmitting/receiving antennas and ground processing equipment. Since GPS technology will be so usable in the future, a specific HSTSS product should be developed for this "GPS+data" approach.

5. MULTIPLE SOURCES AND COMPONENT AVAILABILITY, GOVERNMENT CAPABILITIES AND RIGHTS, AND TRI-SERVICE APPLICATIONS

It is critical that the HSTSS program be crafted to provide several features:

• Multiple Sources and Component Availability: The technologies whose capability for high-g measurement application has been demonstrated must be available for DOD contractors and internal Government users. Since many of the HSTSS technologies will result in actual devices—transmitters, batteries, sensors, etc.—then these items must be available in small quantities and reasonable prices. Most of the HSTSS devices are based upon "microelectronic manufacturing" processes—a single foundry run will produce a wafer with hundreds or thousands of raw devices. These raw die (sensor or electronic) must then be packaged so that they can be easily integrated into MCM or printed wire board assemblies. Minimum charges for foundry and packaging will result in a supply of HSTSS devices that should be managed by the Government and supplied at a replacement-cost basis so as to provide a revolving account. This sounds like a complex process, but it simply amounts to a high-technology "spare parts" point of view. This principle of operation will provide for open competition and multiple sources with assured

availability of key components. Since many of the HSTSS technologies are COTS in nature, availability is assured if the unique features of high-g are simply standard within the commercial product, as in the battery and MCM applications.

- Government Rights and Capability: The T&E responsibility for tactical weapons systems rests with the Government. As such, the Government must retail rights to the HSTSS devices and processes. Additionally, since the private sector may not choose to continue to maintain HSTSS knowledge or capability, then the Government must maintain a limited but reasonable ability to internally design, fabricate, and use HSTSS-based flight measurement systems. It is clear that the programmable MCM systems (or like systems) should be purchased by the Government to assure prototyping, low-rate production capability, and a residual capability.

- Tri-Service Applications: Although the stated purpose of the HSTSS program is centered in high-g Army use, tri-Service needs and applications needs must be addressed. It is clear that due to the "size and configurability" of the HSTSS technologies that many tri-Service needs can be satisfied. The spectrum of gun-launch projectiles and munitions, missiles and rockets, and smart bombs are overlapping, and the utility of multiple sources, component availability, and Government rights and capabilities are important to provide true tri-Service benefits. In the FY96 HSTSS budget, Central Test Experiment and Investment Program (CTEIP) funds have been allotted to establish an HSTSS tri-Service group so that requirements can be identified and incorporated.

6. SUMMARY

The HSTSS philosophy is a multi-faceted approach—but this is required if modern technologies are to be infused into the munition testing sequence in a routine and affordable fashion. The broad-based approach of transmitter, sensor, power supply, and packaging technologies has been demonstrated in the TTD&D phase and must be continued through the acquisition cycle.

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